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Design Study of a Permanent-Magnet Quadrupole Focusing Lattice for a mm-wave Traveling Wave Tube

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Abstract: *Linear beam tubes have traditionally relied on axisymmetric solenoidal or PPM focusing to transversely confine the electron beam. In the particle accelerator community, however, it is well-known that alternating-gradient focusing using sequences of quadrupole magnets, known as "strong focusing", is capable of transporting more current for comparable field strengths [1]. At mm-wavelengths, a key limitation to the peak and average power of vacuum electronics devices stems from the difficulty of control and confinement of high-current density beams. In this paper we summarize an ongoing design study of a strong-focusing lattice employing permanent magnet quadrupoles (PMQs) capable of transporting a sub-mm radius electron beam for vacuum electronics applications. The study has the aim of producing a practical design for an experimental study at NRL for comparing quadrupole lattices with standard ones based on solenoidal periodic permanent magnets (PPMs). In addition, a design code and methodology for designing these PMQ channels is under development.*

Keywords: Magnetic focusing; permanent magnet quadrupole (PMQ); periodic permanent magnet (PPM); traveling-wave tube; linear beam; beam transport.

Design Methodology

Given the beam parameters (current, energy, and emittance), a desired beam size and a desired phase-advance, the half-lattice period (center-to-center distance between two quadrupoles), L, is determined from the following equation:

$$L = \frac{\sigma_0 / 2}{\sqrt{K/a^2 + (\varepsilon / a^2)^2}} \qquad (1)$$

where a is the average beam size, σ_o the phase advance (without space charge), ε the four-times rms un-normalized emittance, and K is the generalized perveance given by $2I/I_o/(\beta\gamma)^3$ [1], I is the beam current, and I_o is the characteristic current for electrons (17.045 kA). Equation (1) follows from the envelope equation under the smooth approximation and the definition of phase advance. For a given beam and a given desired beam size, the limitation on the focusing strength is essentially determined by the requirement to keep the phase advance less than 90° so as not to excite envelope instabilities [1].

For a 380-mA, 16 keV electron beam such as the one produced by an existing electron gun that is a likely candidate for the NRL experimental study, L turns out to be of the order of 5.9 mm. For a 0.5 mm radius beam, the size of the rf structure, whether a helix or a series of coupled cavities, combined with that of the vacuum pipe together require that the inner radius of the magnet be no smaller than 4 mm. These constraints imply a very short aspect ratio for the magnets, resulting in a design in which the magnet fringe fields are important and significantly overlap. The fields of a PMQ are best described by the Halbach model for rare-earth-cobalt PMQs [2], which we use in the design code. An interesting observation is that, due to the fringe field overlap, the effective length of a quadrupole, if defined to include that overlap, is almost independent of the physical length of the magnets and equal to about $0.63L$.

A design code that determines the lattice parameters given a specified beam current, energy, emittance, desired average radius, phase advance, and residual magnetization was written and parameter space was scanned to determine the optimal magnet configuration. Beam size turns out to be the most critical determinant of the lattice. One optimal lattice design is shown in Fig. 1, using magnets of length 1.06 mm with a magnetization 0.8 T.

Once the lattice is chosen, TRACE3d [3] input files are automatically generated to assist in matching the beam from the gun to the transport section. Generally three TRACE3d runs are needed: the first to fine tune a matched

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lattice, the second to design a matching section starting from the output of a MICHELLE [4] simulation of the gun, and the third to transform the beam cross-section back to round at the end of the interaction region, for ease of collection by a depressed collector. The field overlap makes matching a difficult problem, the details of which are omitted from this discussion due to lack of space. Once designed, the data is stored in a format readable by WARP [5], a particle-in-cell code which we in a 2-D *x-y* mode to check the design. At present we observe slight variations in results between WARP and TRACE due to the latter's omission of image forces and nonlinearities and its assumptions of constant emittance. Figure 2 displays a typical WARP output of a PMQ lattice with a round-to-round transformation.

Additional details of the design methodology and additional examples of optimized designs of the beam transport system will be presented.

Acknowledgement

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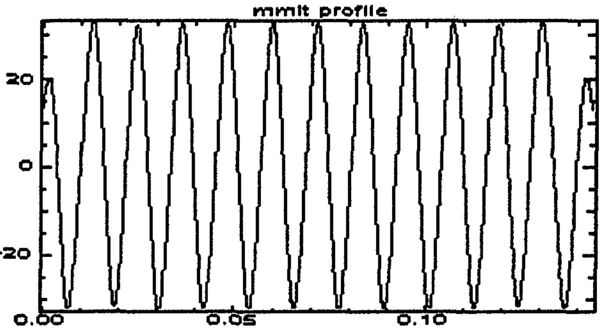

Figure 1. Quadrupole gradient in T/m for design K, as function of longitudinal distance, *s* in m.

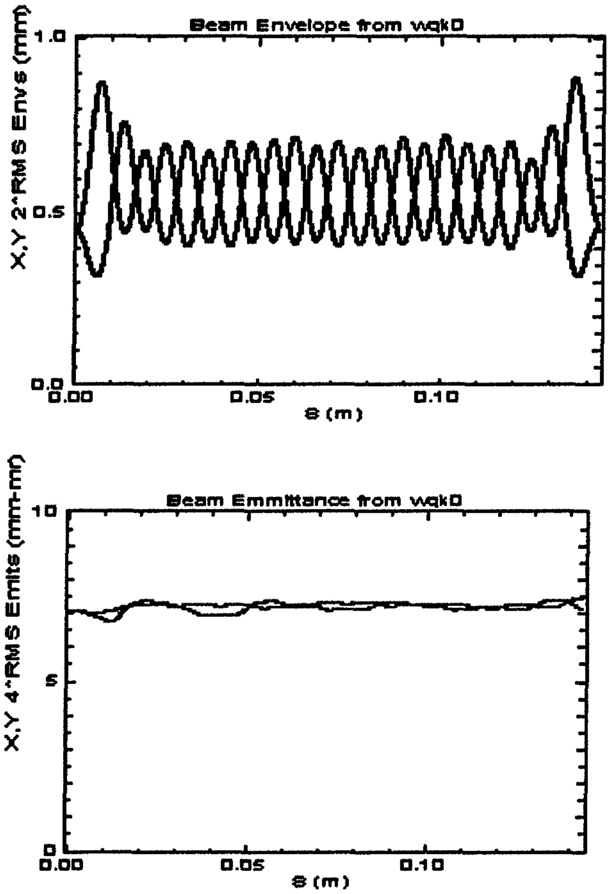

Figure 2. Beam *x* and *y* rms envelopes (top) and emittances (bottom) from WARP (design K), with magnet fringe fields included.